中部土壤所含磷形態與稻穀收量及磷吸取量之關係[1]

林家棻　張愛華　吳懷國[2]

摘要　利用磷形態分佈，以研究土壤中有效態磷供應狀況，過去多以盆栽為主，田間資料缺乏。本試驗之目的在探討中部土壤所含磷形態對於盆栽與田間稻穀收量與磷吸取量之關係，俾供改進稻田磷肥管理與估計磷肥供應之參考。經在本省中部(南投、彰化、雲林及臺中)四種不同類別土壤上，選取20地點，同時舉行盆栽與田間試驗以及室內化驗，所得結果摘要於下：

土壤中全磷及各形態磷含量與土壤母質及其化學性狀有密切關係。粘板岩冲積土全磷含量最高，以 Ca—P 為主。其次為砂頁岩冲積土，以 Fe—P 為主。再次為混合冲積土，則以 Ca—P 與 Fe—P 為主。

稻穀收量或磷吸取量與土壤中各形態磷之關係，經單相關與複相關計算結果，以及栽培前後土壤中各形態磷之變異情形，均顯示水稻所攝取之磷以 Fe—P 為主；但 Ca—P 與有機磷則有干擾作用，尤其在田間更為顯著，因而田間水稻磷吸取量與 Fe—P 之相關係數顯然較盆栽者為低，相對地降低其重要性。

在盆栽情形，水稻磷吸取量與土壤 pH 亦呈極顯著之負相關， 而在田間更與粘土及有機物含量各呈顯著之負相關；相反地， 土壤中 Ca—P 與有機磷之含量則與土壤 pH 、粘土及有機物含量有密切之正相關。因此，土壤中 Ca—P 與有機磷阻礙水稻磷吸取者，可能主要受土壤 pH 與粘土及有機物含量之影響。

綜上所言，水稻磷吸取量確與土壤中Fe—P有關，但其相關程度，在田間不如盆栽者强，此可能因在盆栽不排水情形與田間自然環境之下，由於粘土與有機物呈現不同效應所致。

引　　言

土壤中存在的磷形態，大體上可分為無機態與有機態兩類。Chang 與 Jackson[(4)] 更將無機態分離為鋁結合磷 (Al—P) 、鐵結合磷 (Fe—P) 、鈣結合磷 (Ca—P) 與結核磷 (Occluded—P) 等。張守敬氏[(7)] 并認為水稻對於磷的攝取以 Fe—P 為主， 而陸稻則以 Al—P 為主。 Al-Abbas 與 Baber 兩氏[(1)] 以小米 (millet) 為指示作物時，則認為 Fe—P 有效性最高。 Susuki[(12)] 氏等認為大麥之磷攝取與土壤中 Ca—P 與 Al—P 之關係最為密切。作者等[(13)] 以玉米試驗時， 其磷之攝取受土壤中 Al—P 與 Fe—P 之影響最大。

以上顯示作物對於磷之攝取確與土壤中磷形態之分佈有關。但過去試驗多以盆栽為主，同時土壤中各形態磷多少均有存在。其對於作物收量與磷吸取之複相關關係，尚乏資料，可供參考。本試驗之目的在探討土壤磷形態對於盆栽與田間稻穀收量及磷吸取量之關係，俾供土壤磷素肥力管理與改進土壤有效態磷素測定之參考。

1.試驗報告農試字第七八三號。

2.臺灣省農業試驗所技正、技術員

試 驗 方 法

供試土壤：在本省中部南投、臺中、彰化及雲林四縣選取20點，土壤類別包括砂頁岩冲積土、粘板岩老冲積土、粘板岩新冲積土，以及混合冲積土，其化學性狀及磷形態之分佈如表 1 及 2 。

盆栽試驗：上述每種土壤各設 5 處理即：1.無肥，2.無氮，3.無磷，4.無鉀，及5.三要素，重複兩次共計 200盆，每盆用土 5 公斤，其氮 (N) 、磷 (P_2O_5) 、鉀 (K_2O) 之施用量各 爲 120、80 及 80 kg/ha。水稻品種用臺中65，其他管理照常，連續 4 作水稻。本報告僅選取無磷及三要素兩處理資料討論之。

田間試驗：在上述20地點同時舉行田間試驗，本試驗中氮、磷、鉀施用量各分爲 3 平準，組合爲 8 處理。施肥法中以磷肥悉數作基肥施用；氮肥以25%作基肥，30%作第一次追肥，25%作第二次追肥，其餘20%作穗肥；鉀肥則20%作基肥，其餘80%平分兩次，以追肥施用之。氮肥用硫酸錏，磷用過磷酸鈣，鉀用氯化鉀，小區面積爲2.5×4＝10 平方公尺，隨機排列，4 重複，其他照當地習慣法行之。本報告中僅取無磷區(N 60 kg/ha. P_2O_5 O kg/ha 及 K_2O 40 kg/ha)及施磷區(N 60 kg/ha P_2O_5 80 kg/ha K_2O 40 kg/ha) 所得資料討論之。

土壤分析：1. pH 用玻璃電極法 (土：水＝1 ： 1) (14) ，2.有機物用 Walkeley 與 Black 氏法 (14) ，3.機械分析用浮秤法(Hydrometer method) (14) ，4.陽離子交換能量與交換性陽離子用醋酸銨法 (14) ， 5.土壤中全磷用過氯酸分解後，用鉬藍法并以 Ascorbic acid 作還元劑比色測定之 (3) 。

表1. 供試土壤之化學性狀

Table 1. The chemical characteristics of the soils tested

Soil No.	Location	pH	Texture	Mechanical analysis			Organic matter %	CEC me/100 g	Exchangeable cations me/100 gm			Free Fe %	Extractable Al ppm
				Clay %	Silt %	Sand %			K	Ca	Mg		
Sandstone and shale alluvial soils													
NT-1	南投草屯碧州里	5.3	SiCL	37.9	48.0	14.1	2.4	13.1	0.22	5.49	1.49	1.47	29.6
NT-2	南投草屯新庄里	4.7	L	21.9	40.0	38.1	2.3	11.9	0.13	4.89	1.15	0.96	30.8
NT-3	南投南投營南里	7.5	SiCL	29.9	56.0	14.1	3.1	16.3	0.20	28.44	2.47	1.56	14.7
NT-4	南投南投營南里	5.4	CL-C	39.9	38.0	22.1	3.7	22.9	0.28	12.97	3.62	1.56	36.6
NT-5	南投南投營北里	5.6	L	23.9	46.0	30.1	2.2	15.6	0.24	7.24	2.14	1.11	22.5
Slate recent alluvial soils													
CH-1	彰化田尾新生村	7.2	SiC	35.9	48.0	16.1	2.7	9.7	0.09	8.58	1.52	1.05	11.8
CH-2	彰化田尾陸豐村	7.6	SiCL	35.9	54.0	10.1	3.2	10.5	0.14	34.43	2.14	0.95	17.1
YL-1	雲林西螺振興里	6.2	SiCL	37.9	46.0	16.1	2.6	11.9	0.19	6.94	2.24	1.02	15.0
YL-2	雲林西螺振興里	5.8	SiC	43.9	48.0	8.1	2.9	11.9	0.32	6.34	2.07	0.99	22.9
YL-5	雲林西螺振興里	6.1	SiC	39.9	46.0	14.1	4.0	15.6	0.29	10.58	2.83	0.99	19.2
YL-4	雲林西螺振興里	7.6	L	21.9	40.0	38.1	3.4	11.7	0.19	32.44	2.39	0.72	9.6
YL-3	雲林西螺振興里	6.9	CL	29.9	46.0	24.1	3.0	10.0	0.11	6.99	1.44	0.72	15.3

Slate older alluvial soils

CH-3	彰化北斗中寮里	7.2	SiCL	29.9	52.0	18.1	2.6	13.3	0.14	15.97	1.07	0.96	9.1
CH-4	彰化北斗中寮里	7.5	SiL	19.9	54.0	26.1	2.4	10.7	0.09	25.45	1.45	0.81	6.2
CH-5	彰化北斗中寮里	7.2	SiCL	31.9	48.0	20.1	3.3	14.7	0.19	17.22	1.64	1.02	6.5

Mixed alluvial soils

TC-1	臺中清水菁埔里	5.3	L	23.9	40.0	36.1	3.0	9.5	0.23	3.99	1.04	0.30	21.2
TC-2	臺中清水菁埔里	5.4	L	13.9	40.0	46.1	2.0	5.9	0.14	2.69	0.77	0.21	25.7
TC-3	臺中清水菁埔里	4.9	L	21.9	46.0	30.1	2.6	8.3	0.10	3.19	0.75	0.42	26.0
TC-4	臺中沙鹿鹿峰里	5.7	SL	13.9	28.0	58.1	2.5	8.1	0.07	4.49	1.20	0.93	10.5
TC-5	臺中沙鹿鹿峰里	6.3	L	17.9	38.0	44.1	1.5	7.0	0.10	5.34	1.57	0.93	7.5

表2. 供試土壤中各形態磷之分佈情形

Table 2. Amounts of soil phosphorus fractions of the soils tested, ppm

Soil No.	Total —P	Al—P	Fe—P	Ca—P	Occluded—P	Organic—P
Sandstone & shale alluvial soil						
NT—1	440	27.4	156.3	38.6	117.5	100.8
NT—2	820	66.7	373.8	158.0	131.8	89.7
NT—3	650	57.4	103.8	140.3	183.8	164.7
NT—4	450	16.5	146.5	45.0	75.0	167.0
NT—5	650	45.6	264.5	131.3	139.0	69.6
Slate recent alluvial soil						
CH—1	800	30.6	80.3	455.0	88.0	146.1
CH—2	800	20.5	16.0	490.0	95.0	178.5
YL—1	675	21.5	110.0	317.0	92.8	133.7
YL—2	770	35.3	177.3	317.0	114.5	125.9
YL—3	755	19.8	121.3	334.0	77.5	202.4
YL—4	850	49.9	23.5	515.0	190.0	71.6
YL—5	725	38.1	83.8	436.0	65.8	101.3
Slate older alluvial soil						
CH—3	1040	73.8	143.0	567.0	112.5	143.7
CH—4	770	25.9	24.5	548.0	75.0	96.6
CH—5	875	47.5	105.8	482.0	93.3	146.4

Mixed alluvial soil

TC—1	675	83.8	298.5	181.0	10.0	101.7
TC—2	345	27.3	45.0	184.0	32.0	56.7
TC—3	450	29.8	110.8	191.0	36.0	82.4
TC—4	400	14.9	79.5	139.0	70.0	96.6
TC—5	380	13.3	59.5	171.5	48.5	87.2

6.無機態磷之分離則用 Chang and Jackson [4] 法，7. 有機態磷則由全磷與各無機態磷總和之差求得之， 8.游離鐵用 $Na_2S_2O_4$-EDTA 法測定之 [2] ，9.可抽出鋁用 IN NH_4OAC pH 4.8 抽出後用 Aluminon 比色法測定之。

植物分析：水稻收穫乾燥稱量後，分穀藁兩部份，其中全氮用 Kjedahl's 法， 測定磷、鉀時，則先將植物樣本乾灰化後（550°C），磷用釩酸銨法，鉀用焰光法測定之 [15] 。

結 果 與 討 論

一、土壤類別間磷形態之分佈及其與土壤化學性狀之關係：表3.示土壤類別間之全磷含量，以粘板岩冲積土最高，其次爲砂頁岩冲積土，再次爲混合冲積土。就磷形態之分佈而言，砂頁岩冲積土以鐵結合磷爲主，其他冲積土包括粘板岩新冲積土，粘板岩老冲積土及混合冲積土均以鈣結合磷爲主，鐵結合磷（包括結核磷）爲副。鋁結合磷在各類土壤中所佔全磷之百分比均低，約在 4 ～ 7 %間。有機磷則在14～20%間。此與張守敬氏 [5] 研究本省主要土壤類別間磷形態之分佈甚爲接近。

表3. 供試土壤類別間磷形態之分佈情形

Table 3. Average amounts of soil phosphorus fractions of different soils

土壤類別 Soil	全磷 Total -P	鋁結合磷 Al-P	鐵結合磷 Fe-P	鈣結合磷 Ca-P	結核磷 Occluded-P	有機磷 Organic-P
			ppm			
砂頁岩冲積土 Sandstone & shale alluvial soils	602.0 (100)	42.7 (7.1)	209.0 (34.7)	102.6 (17.0)	129.4 (21.5)	118.4 (19.7)
粘板岩新冲積土 Slate recent alluvial soils	767.0 (100)	30.8 (4.0)	87.5 (11.4)	409.1 (53.3)	103.4 (13.5)	137.1 (17.9)
粘板岩老冲積土 Slate older alluvial soils	895.0 (100)	49.0 (5.5)	91.1 (10.2)	532.3 (59.5)	93.6 (10.5)	128.9 (14.4)
混合冲積土 Mixed alluvial soils	450.0 (100)	33.8 (7.5)	118.7 (26.4)	173.3 (38.5)	39.3 (8.7)	84.9 (18.9)

表4.示土壤中 Al—P 與 Fe—P 均與土壤 pH, CEC, 及交換性鎂有關， Ca—P 則與 pH, 游離鐵及粘土含量有關。結核磷與 pH、游離鐵及交換性鈣有關，有機磷則與 Clay, 有機物及 pH 有關。由此顯示土壤中各形態磷之分佈除受母質之影響外，其與土壤化學性狀亦有密切關係。表3.示粘板岩冲積土所含 Ca—P 較其他冲積土高出數倍，如何改進土壤化學性狀促使其有效化，誠有加以研究之必要。

表4. 土壤磷形態與化學性狀之相關係數及其迴歸方程式

Table 4. Correlation coefficient as well as regression equation between forms of soil phosphorus and some chemical properties of the soils

Dependent variable	Independent variable	Correlation coefficient	Regression equation
Al—P	Exch. Mg	−0.29	Y=−8.08Mg+51.43
	pH×CEC×Mg	0.58**	Y=4.36 CEC−26.32Mg+31.27
	pH×CEC×Mg	0.61*	Y=4.32 pH+4.73 CEC−29.09Mg−1110.91
Fe—P	pH	−0.63**	Y=−60.56 pH+505.90
	pH×CEC	0.69**	Y=−61.71 pH+6.78 CEC +432.27
	pH×CEC×Mg	0.76**	Y=−52.54 pH+17.01 CEC−68.99Mg+373.39
Ca—P	pH	0.78**	Y=138.88pH−578.78
	pH×Fe	0.86**	Y=149.95 pH−181.47 Fe−39126.20
	pH×Clay×Fe	0.90**	Y=147.46 pH+6.12 Clay−268.02 Fe−38563.39
Occluded—P	Fe	0.57**	Y=74.63 Fe+22.69
	pH×Fe	0.64**	Y=14.07 pH+68.17 Fe−3686.05
	pH×Ca×Fe	0.71**	Y=−5.10 pH+2.38 Ca+59.81 Fe+1354.55
Organic—P	Clay	0.74**	Y=3.27 Clay+24.33
	Clay×O. M.	0.80**	Y=2.26 clay+26.77 O. M. −20.84
	pH×Clay×O M	0.83**	Y=8.49 pH+2.29 clay+22.69 O. M. −2254.37

二、土壤磷形態與稻谷收量及磷吸取量之單相關關係：張守敬氏等[9]認爲水稻以吸取 Fe—P 爲主，乃由於土壤中 Fe—P 含量較 Al—P 爲多，而其表面活性比 (Specific surface activity) 較 Ca—P 爲大；同時 Ca—P 多集中於粗粒部分，Patrick Mikkelsen[11] 認爲稻田浸水後，提高土壤磷肥有效度者乃由於高價鐵結合磷，在浸水之下，還原爲膠狀低價鐵結合磷，而增加其表面積提高水稻吸取機會。表 5.示在盆栽試驗稻谷收量與 Fe—P 均爲正相關，且多達顯著平準，但與 Ca—P 則多爲顯著之負相關，而與其他形態磷之相關係數多未達顯著平準。在田間情形之下，稻谷收量與 Fe—P 亦爲正相關，但多不顯著，僅在第一期作稻谷收量百分比出現顯著之正相關，至於稻谷收量與 Ca—P 仍爲負相關。其在第二期作多達顯著平準，此外，稻谷收量百分比與 Al—P 在第一期作時亦出現顯著之負相關。

表6.示在盆栽情形之下，水稻磷吸取量仍與土壤中 Fe—P 含量成極顯著之正相關，與土壤中 Ca—P 則爲極顯著之負相關，田間試驗結果亦然，但其相對之相關係數則普遍降低，其中尤以Fe—P 爲然，此可能因 Fe—P 有效度之增加，主要受稻田灌水，形成還原狀態，使高價還原爲低價鐵而提高其溶解度，各地田間試驗，水分管理未必一致，因而降低其與水稻磷吸取之相關係數。此外，或因田間情形之下，有機磷與水稻磷吸取亦多達顯著之負相關，因此亦影響水稻對於 Fe—P 之攝取，而減低其相關係數。又據張守敬氏[8]引述 Ishizuka 與 Tanaka 研究之結果，認爲磷肥不似氮、鉀肥

表5. 土壤磷形態與稻谷收量之單相關係數

Table 5. Simple correlation coefficient between soil P-fraction and grain yield

P—fraction	1st Crop			2nd Crop		
	—P	+P	—P/+P×100	—P	+P	—P/+P×100
			Pot experiment			
Al—P	− 0.06	− 0.01	− 0.11	0.19	− 0.07	0.33
Fe—P	0.49*	0.53*	0.11	0.62**	0.43	0.31
Ca—P	− 0.64**	− 0.59**	− 0.32	− 0.24	− 0.58**	0.21
Occluded—P	− 0.21	− 0.07	− 0.31	− 0.10	0.39	− 0.48*
Organic—P	0.06	0.12	− 0.11	0.18	0.08	0.08
			Field experiment			
Al—P	− 0.01	− 0.13	− 0.61**	− 0.08	− 0.18	0.43
Fe—P	0.09	0.21	0.49*	0.28	0.22	0.04
Ca—P	− 0.29	− 0.26	− 0.07	− 0.65**	− 0.65**	0.39
Occluded—P	0.08	0.12	− 0.03	− 0.02	− 0.17	− 0.10
Organic—P	− 0.32	− 0.32	0.04	− 0.43	0.42	0.17

表6. 土壤磷形態與水稻吸取量之單相關係數

Table 6. Simple correlation coefficient between soil P-fraction and P-uptake of rice plant

P-fraction	Pot experiment				Field expriment			
	1st Crop		2nd Crop		1st Crop		2nd Crop	
	—P	+P	—P	+P	—P	+P	—P	+P
Al—P	0.08	− 0.009	0.11	− 0.05	− 0.19	− 0.04	0.01	− 0.09
Fe—P	0.67**	0.66**	0.74**	0.62**	0.11	0.29	0.47*	0.38
Ca—P	− 0.70**	− 0.75**	− 0.62**	− 0.85**	− 0.43	− 0.61**	− 0.80**	− 0.80**
Occluded—P	− 0.22	− 0.23	− 0.06	0.01	− 0.38	− 0.43	− 0.12	− 0.12
Organic—P	− 0.11	− 0.20	− 0.02	− 0.31	− 0.22	− 0.49*	− 0.49*	− 0.52*

，即使施用過量，僅提高稻體中磷濃度，但不顯著降低稻谷收量，因此，土壤中若干形態磷與稻谷收量或磷吸取量成顯著負相關者，可能受土壤其他性狀之影響，容待後節討論之。

三、土壤磷形態與稻谷收量及磷吸取量之複相關關係：土壤中各形態磷包括 Al—P, Fe—P, Ca—p，結核磷及有機磷多少均有存在，若全部 5 種形態磷均加以考慮，則除田間第一期作外，稻谷收量或磷吸取量與土壤各形態磷之複相關係數均達到顯著平準(表 7)。為明瞭各形態磷之相對重要性，逐漸刪

表7. 土壤磷形態與盆栽及田間稻谷收量及磷吸取量之複相關係數

Table 7. Multiple correlation coefficient between soil P-fraction and grain yield as well as P-uptake of rice plant*

Crop	Treat-ment	Dependent variable	Independent variable	R	Indepen-dent variable	R	Indepen-dent variable	R	Indepen-dent variable	R	Indepen-dent variable	R	Inde-pen-dent Vari-able	R
							Pot Experiment							
1st	−P	Yield	2×3×4×5×6	0.75*	2×3×4×6	0.74**	2×3×4	0.71**	3×4	0.68**	2×3	0.67**		
	+P	Yield	2×3×4×5×6	0.74*	2×3×4×6	0.74**	2×3×4	0.70**	3×4	0.66**	2×3	0.67**		
2nd	−P	Yield	2×3×4×5×6	0.73*	2×3×4×6	0.72*	2×3×4	0.69**	3×4	0.62**	2×3	0.66**		
	+P	Yield	2×3×4×5×6	0.83**	2×3×4×6	0.78**	2×3×4	0.78**	3×4	0.61**	2×3	0.59**		
1st	−P	P-uptake	2×3×4×5×6	0.84**	2×3×4×5	0.84**	2×3×4	0.83**	3×4	0.81**	2×3	0.78**		
	+P	P-uptake	2×3×4×5×6	0.89**	2×3×4×5	0.89**	2×3×4	0.88**	3×4	0.84**	2×3	0.83**		
2nd	−P	P-uptake	2×3×4×5×6	0.86**	2×3×4×5	0.85**	2×3×4	0.85**	3×4	0.81**	2×3	0.85**		
	+P	P-uptake	2×3×4×5×6	0.94**	2×3×4×5	0.93**	2×3×4	0.91**	3×4	0.89**	2×3	0.81**		
							Field Experiment							
1st	−P	Yield	2×3×4×5×6	0.42	3×4×5×6	0.42	3×4×6	0.39	4×6	0.39	3×4	0.29	2×3	0.13
	+P	Yield	2×3×4×5×6	0.43	3×4×5×6	0.43	3×4×6	0.39	4×6	0.38	3×4	0.28	2×3	0.21
2nd	−P	Yield	2×3×4×5×6	0.72*	3×4×5×6	0.72*	3×4×6	0.72**	4×6	0.72**	3×4	0.65**	2×3	0.43
	+P	Yield	2×3×4×5×6	0.73*	3×4×5×6	0.72*	3×4×6	0.71**	4×6	0.71**	3×4	0.65**	2×3	0.45
1st	−P	P-uptake	2×3×4×5×6	0.56	3×4×5×6	0.55	3×4×6	0.46	4×6	0.45*	3×4	0.44	2×3	0.34
	+P	P-uptake	2×3×4×5×6	0.78**	3×4×5×6	0.78**	3×4×6	0.71**	4×6	0.71**	3×4	0.61**	2×3	0.40
2nd	−P	P-uptake	2×3×4×5×6	0.87**	3×4×5×6	0.87**	3×4×6	0.87**	4×6	0.86**	3×4	0.81**	2×3	0.57
	+P	P-uptake	2×3×4×5×6	0.89**	3×4×5×6	0.87**	3×4×6	0.87**	4×6	0.87**	3×4	0.80**	2×3	0.56*

* Independent variable, 2, 3, 4, 5, and 6 indicates Al—P, Fe—P, Ca—P, Occluded—P, and Organic—P, respectively.
"R" stands for multiple correlation coefficient. *shows significant at 5% level, and ** at 1% level.

除其次重要者，則發現稻谷收量或磷吸取量與4種形態磷之複相關係數幾乎與5種形態磷者完全相同，此外，其與三種形態磷或二種形態磷所得之複相關係數，雖然略有降低，由於獨立變數減少，自由度增加，因而並不影響其顯著平準。

若就三種形態磷而言，在盆栽情形之下，稻谷收量或磷吸取量受土中 Al—P, Fe—P, 及 Ca—P 之影響最大；而在田間情形之下，則以 Fe—P, Ca—P 及有機磷最爲重要。 若就二種形態磷而言，在盆栽之下，則以 Fe—P×Ca—P, 或 Al—P×Fe—P ，兩者對於稻谷收量或磷吸取量， 幾乎具有同等的影響力；但在田間之下，則以 Ca—P× 有機磷最爲重要，其次則爲 Fe—P×Ca—P, 若以 Al—P×Fe—P 所得之複相關係數與 Fe—P×Ca—P 所得者比較時，則顯然降低，且多未達顯著平準。過去本省稻田磷需要量之測定多用 Bray 氏第一法 (0.025NHCl-0.03N NH_4F) ，該法所抽取之磷主爲 Al—P 及 Fe—P, 應用於田間，尤其鈣質粘板岩冲積土之稻田，多未盡理想，其原因可能在此。

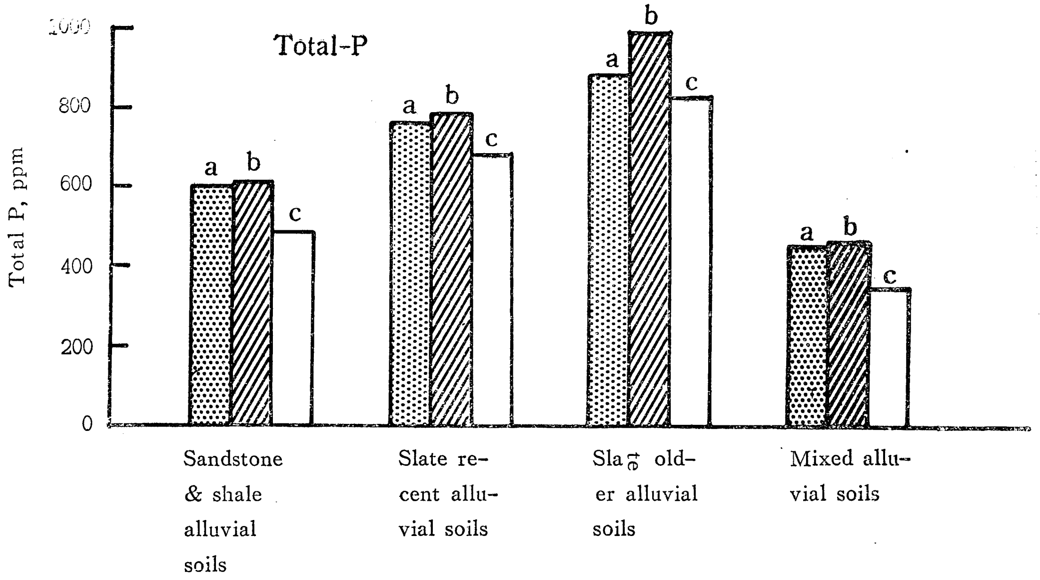
土壤中三種形態磷之相對重要性，更以 β-coefficient 示之如表8。所謂 β 係數乃以迴歸係數乘個別標準偏差求得之 [10] ， $\beta_{y \cdot x}=b_{y \cdot x}\left(\frac{Sx}{Sy}\right)$. β 係數有正有負。數值愈大者，其重要性愈高。在盆栽情形之下，Fe—P 之 β 係數均爲正值，且較其他兩形態磷爲高。Al—P 與 Ca—P 之 β 係數均爲負值，兩者或高或低，或相等，差異不一致，因此，在盆栽情形之下，以 Fe—P×Ca—P, 或以 Al—P×Fe—P 與稻谷收量或磷吸取量之複相關係數幾乎不相上下，均達到顯著平準；但在田間之下，其情形則不然，三種形態磷中 (Fe—P, Ca—P, 及有機磷) 除第一期作其複相關係數未達顯著平準，不予討論外，均以 Ca—P 之 β 係數最高，其次爲有機磷，而 Fe—P 則遠低於前兩者，而 Ca—P 與有機磷均爲負值，甚至有時 Fe—P 之 β 係數亦爲負值。過去從事土壤磷有效指數時，很少注意負效應的問題，此似可說明利用土壤速測估計稻田磷供應之困難所在。

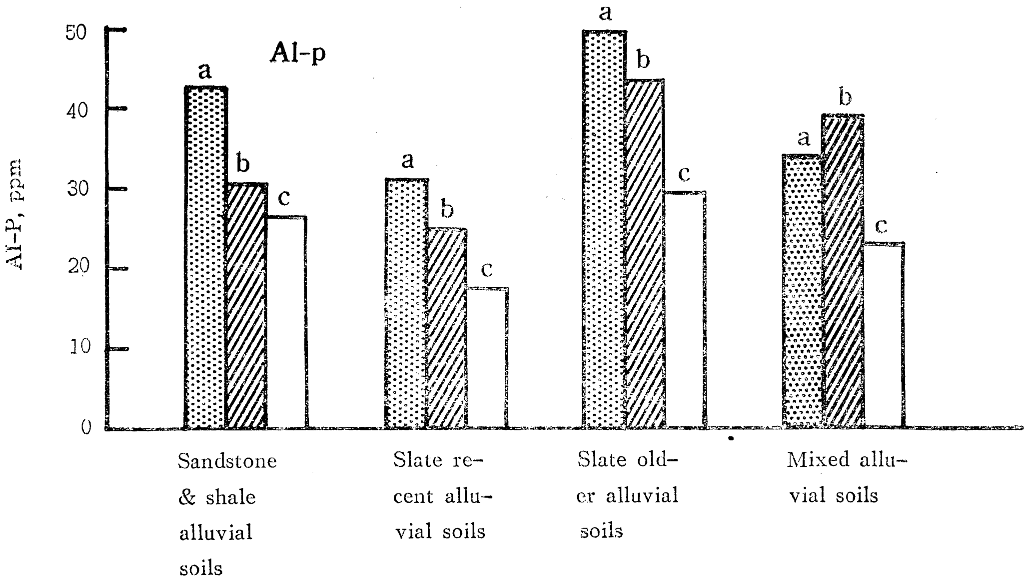
表8. 土壤個別磷形態對於稻谷收量及磷吸取量之相對重要性

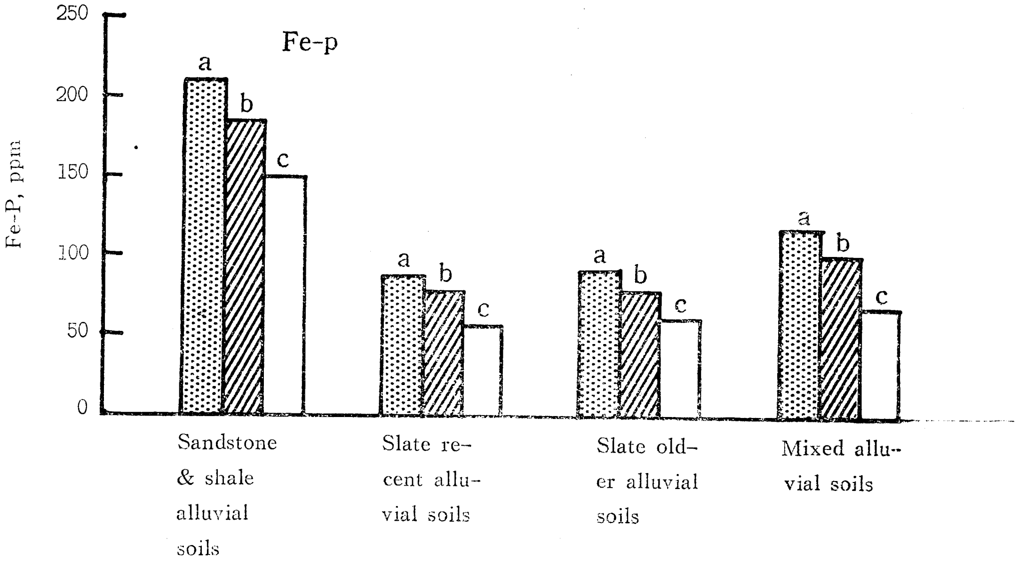
Table 8. Relative importance of individual soil P-fraction affecting grain yield and P-uptake of rice plant

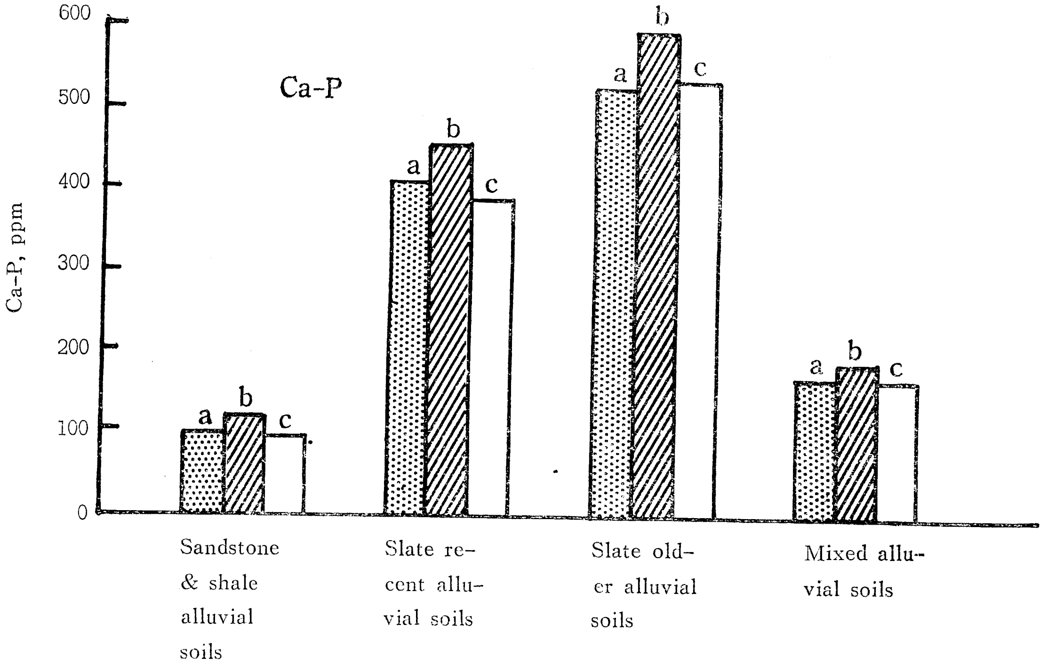
Crop	Treat-ment	Dependent variable	Pot experiment Independent variable			Field experiment Independent variable		
			Al—P	Fe—P	Ca—P	Fe—P	Ca—P	Organic—P
			Beta coefficient					
1st	－P	Yield	−0.34	0.54	−0.34	−0.05	−0.25	−0.27
	＋P	Yield	−0.35	0.65	−0.25	0.11	−0.15	−0.27
2nd	－P	Yield	−0.44	1.01	0.27	−0.02	−0.59	−0.30
	＋P	Yield	−0.31	0.46	−0.33	−0.10	−0.63	−0.28
1st	－P	P-uptake	−0.27	0.67	−0.36	−0.10	−0.45	−0.13
	＋P	P-uptake	−0.39	0.73	−0.37	0.01	−0.53	−0.36
2nd	－P	P-uptake	−0.41	0.92	−0.15	0.12	−0.67	−0.32
	＋P	P-uptake	−0.30	0.54	−0.56	0.01	−0.71	−0.35

四、栽培前後盆栽土壤中磷形態之變異：供試土壤經連續4作水稻後，盆中土壤經風乾，磨細後 (通過 0.5mm篩孔) ，選取無磷與施磷兩處理，分別測定各形態磷之分佈情形， 如圖1.其中顯示土壤中全磷含量，若不施用磷肥，栽培後確較栽培前降低，而施磷者則有提高之趨向。 土壤中 Al—


Total-P
Total P, ppm
1000
800
600
400
200
0
a
b
c
Sandstone & shale alluvial soils
Slate recent alluvial soils
Slate older alluvial soils
Mixed alluvial soils


Al-p
Al-P, ppm
50
40
30
20
10
0
a
b
c
Sandstone & shale alluvial soils
Slate recent alluvial soils
Slate older alluvial soils
Mixed alluvial soils


Fe-p
Fe-P, ppm
250
200
150
100
50
0
a
b
c
Sandstone & shale alluvial soils
Slate recent alluvial soils
Slate older alluvial soils
Mixed alluvial soils


Ca-P
Ca-P, ppm
600
500
400
300
200
100
0
a
b
c
Sandstone & shale alluvial soils
Slate recent alluvial soils
Slate older alluvial soils
Mixed alluvial soils

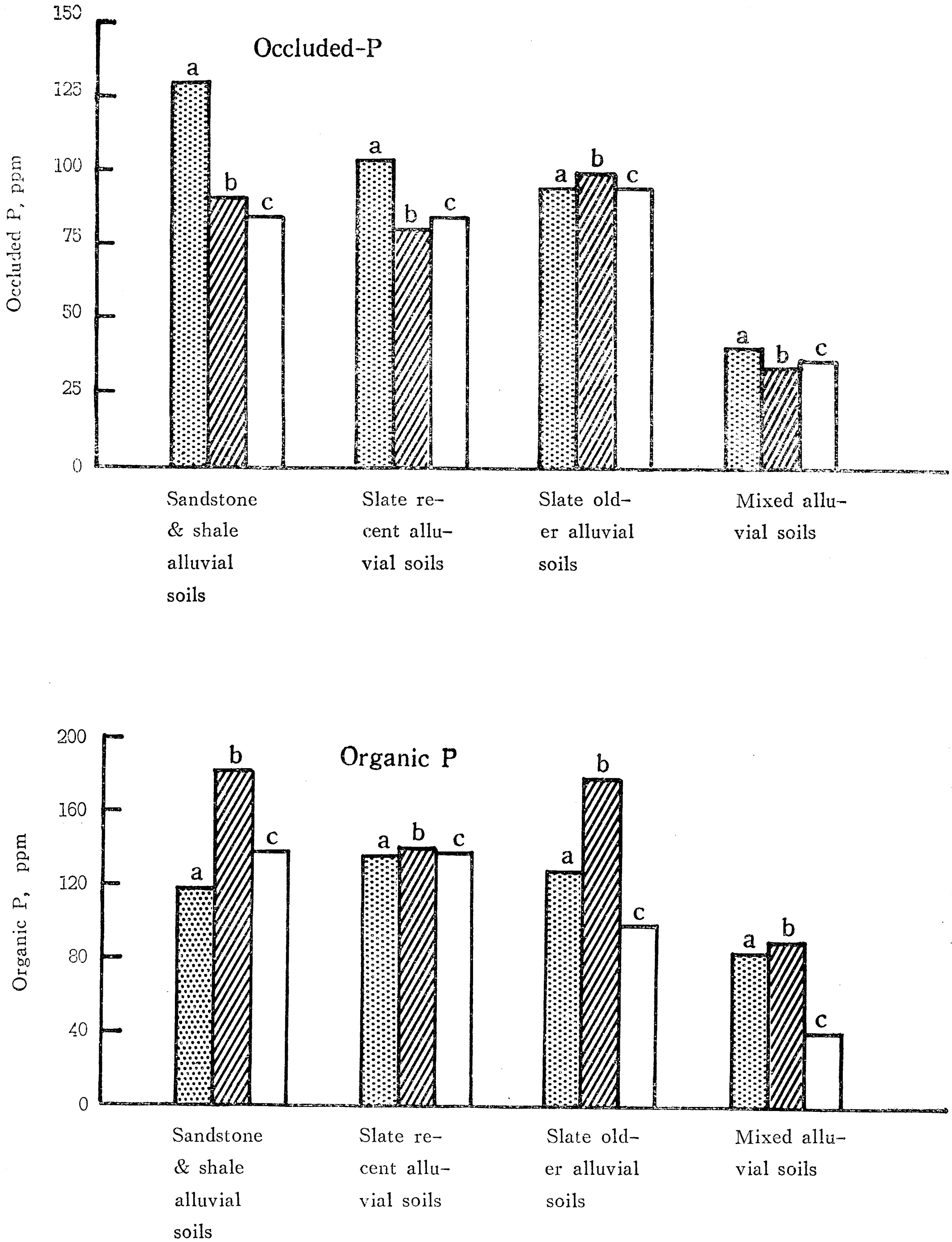


Fig. 1. Average amount of various forms of soil phosphorus before and after 4 consecutive crops of rice plant

a=before cropping, b=after cropping with P added, c=after cropping without P added.

P 與 Fe—P, 不施磷者， 栽培後均較栽培前爲低，即使施磷亦有同樣趨勢， 僅混合冲積土例外，Al —P 有提高趨向。土壤中 Ca—P, 施磷者多增加，無磷者，栽培後其 Ca—P 含量仍與栽培前相差無幾。土壤中結核磷，施磷與否，栽培後兩者間相差無幾，但多較栽培前爲低，只有粘板岩老冲積土例外。土壤中有機磷，經栽培後，施磷者均增加，無磷者則因土壤類別而異，不甚一致。

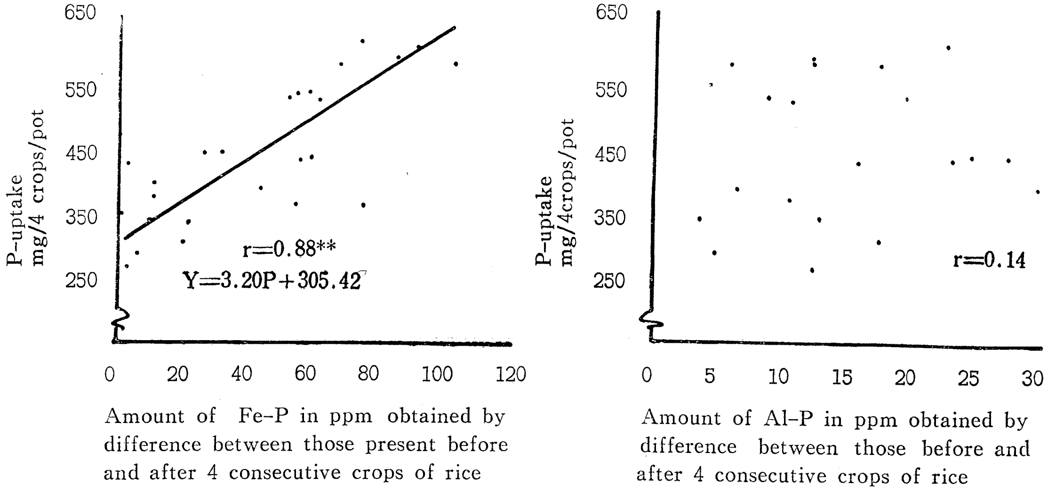


Fig. 2. Relationship of P-uptake of rice plant to soil Fe-P or Al-P obtained by difference between those present before and after 4 crops of rice in pot culture

綜上而言，不施磷時，栽培後土壤中全磷含量均較栽培前降低，似可斷定由於水稻攝取所致。至於栽培前後其他形態磷之變異，是否與水稻攝取有關 ，頗難判定 。 由於本試驗中並未設有不栽培處理，土壤中磷形態之變異，可受栽培期間許多因子之影響，諸如土壤 pH、 氧化還原電位、釋放與固定等因子。但從以上結果顯示，不施磷時， 栽培後土壤中 Al—P 與 Fe—P 普遍地較栽培前爲低。若栽培後，該兩形態磷之減少與水稻對於磷之攝取有關，則栽培前後各該形態磷之差必與水稻磷吸取量有顯著關係。 圖2.顯示水稻磷之攝取確與栽培後土壤中 Fe—P 之減少有極顯著之正相關， 但與 Al—P 之關係則不顯明。換言之，栽培後土壤中 Fe—P 之減低， 極可能由於水稻攝取所致。 此與張守敬氏 [6,7] 所得結果正相符合，渠以不栽培與栽培水稻後， 土壤中 Al—P、Fe—P 及 Ca—P 之變化另以同位元素 P^{32} 追蹤不栽培與栽培水稻後， 在上列三種形態磷中之 P^{32} 分佈情形，均顯示水稻以吸取 Fe—P 爲主。

五、土壤化學性狀對於水稻磷攝取之關係：土壤中所存在各形態磷，除受土壤母質之影響外，尙與土壤之化學性狀有密切之關係（表４），若單憑土壤磷形態與稻穀收量或磷吸取量之相關，很容易導致不正確的觀念，如土壤中 Ca—P 與有機磷對於稻穀收量或磷吸取量均有負的效應，究竟係受磷形態的影響，抑或與土壤其他化學性狀有關，或兩者兼有，値得加以探討。

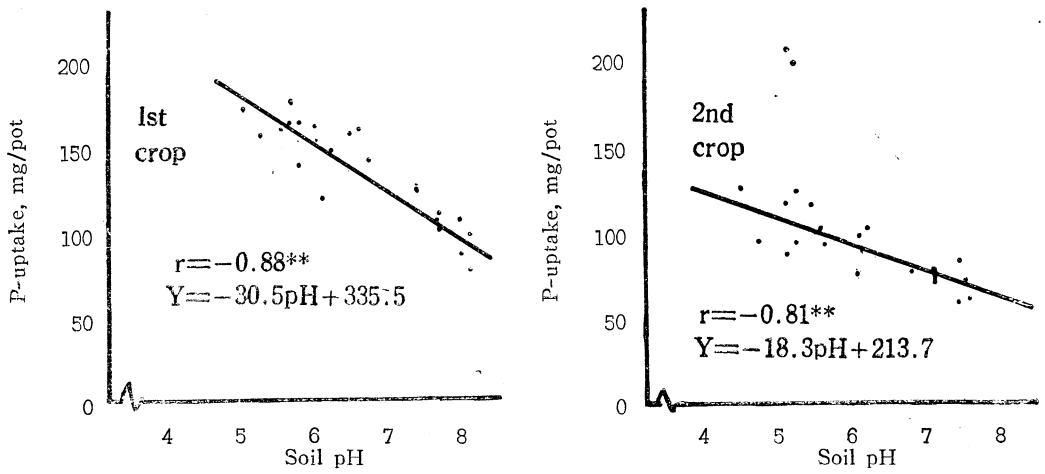
表9.示在盆栽與田間情形之下， 兩者水稻之磷吸取量與土壤 pH 多有極顯著之負相關， 而土壤 Ca—P 與 pH 亦有極顯著之正相關（表４），因此，土壤 Ca—P 多時， 水稻磷之吸取量減少，土壤 pH 亦爲重要影響因子之一。從圖3.示在盆栽施磷之下，土壤 pH >7.0時，水稻磷吸取量多降低，在田間施磷之下，亦有類似趨向，但不及盆栽的明顯，可能又受其他因子的影響。 李子純氏 [16] 等研究中部粘板岩冲積土性質與水稻生長之關係時，亦認爲土壤 pH 與稻株中磷含 量有極顯著之負相關，而土壤溶液 pH與 HCO_3^-, Ca^{2+}, Mg^{2+}, 又呈顯著之正相關，因此，渠等認爲土壤 pH 高時，影響水稻生長者，可能由此溶液中高濃度之 HCO_3^-, Ca^{2+}，Mg^{2+} 等離子所致。

表9. 土壤化學性狀與水稻磷攝取量之相關係數

Table 9. Correlation coefficient between soil chemical properties and P-uptake of rice plant

Soil factor	Pot experiment				Field experiment			
	1st Crop		2nd Crop		1st Crop		2nd Crop	
	−P	+P	−P	+P	−P	+P	−P	+P
pH	−0.88**	−0.88**	−0.78**	−0.81**	−0.39	−0.61**	−0.64**	−0.66**
Clay	0.16	0.13	0.22	−0.04	−0.42	−0.63**	−0.19	−0.40
O. M.	0.003	0.14	0.08	−0.31	−0.20	−0.47*	−0.48*	−0.52*
pH×Clay	0.93**	0.92**	0.85**	0.81**	0.54*	0.83**	0.71**	0.73**
pH×Clay×O. M.	0.93**	0.92**	0.86**	0.83**	0.55	0.83**	0.73**	0.76**

Pot Experiment



Field Experiment

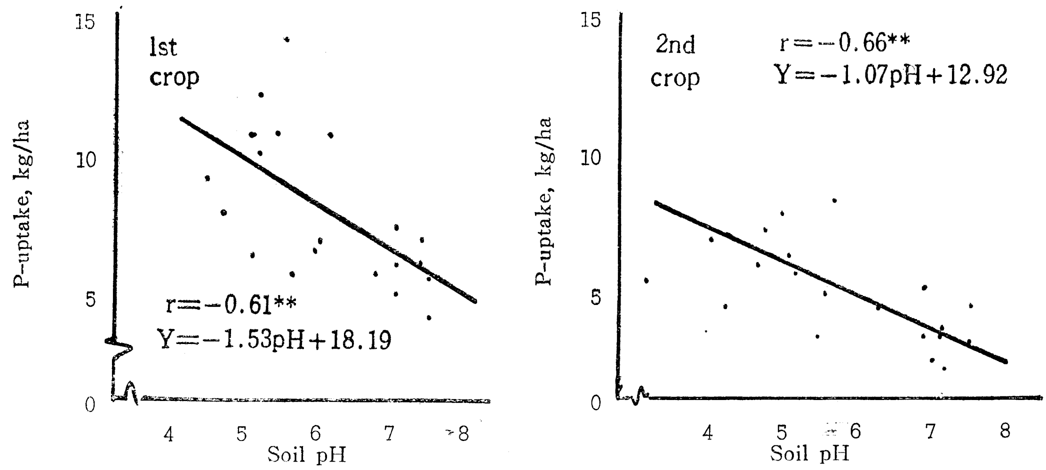


Fig. 3 Relationship between soil pH and P-uptake of rice plant

在盆栽之下，水稻磷吸取量與土壤中粘土或有機物含量之關係不顯明；但在田間之下，則多呈顯著之負相關。此可能由於粘土與有機物含量高之土壤，其土壤內部排水多未達理想，在水稻栽培期中嫌氣情形之下，有機物分解不完全所產生中間產物，抑制水稻對於磷之吸取；而在盆栽之下，由於所用之盆未設有排水裝置，因而不易顯現有機物與粘土含量之影響。從表4.可知土壤有機磷對於粘土與有機物含量有密切之複相關關係，因此，在田間之下，土壤有機磷與水稻磷吸取量呈負相關者，毋寧謂為由於土壤有機物或粘土含量之影響。

土壤中 Ca—P 與有機磷各與土壤 pH 及粘土含量有密切之關係，因此，水稻磷吸取量與二因子（pH ×粘土）之複相關係數，顯然較其個別之單相關係數為高，但水稻磷吸取量與三因子（pH×

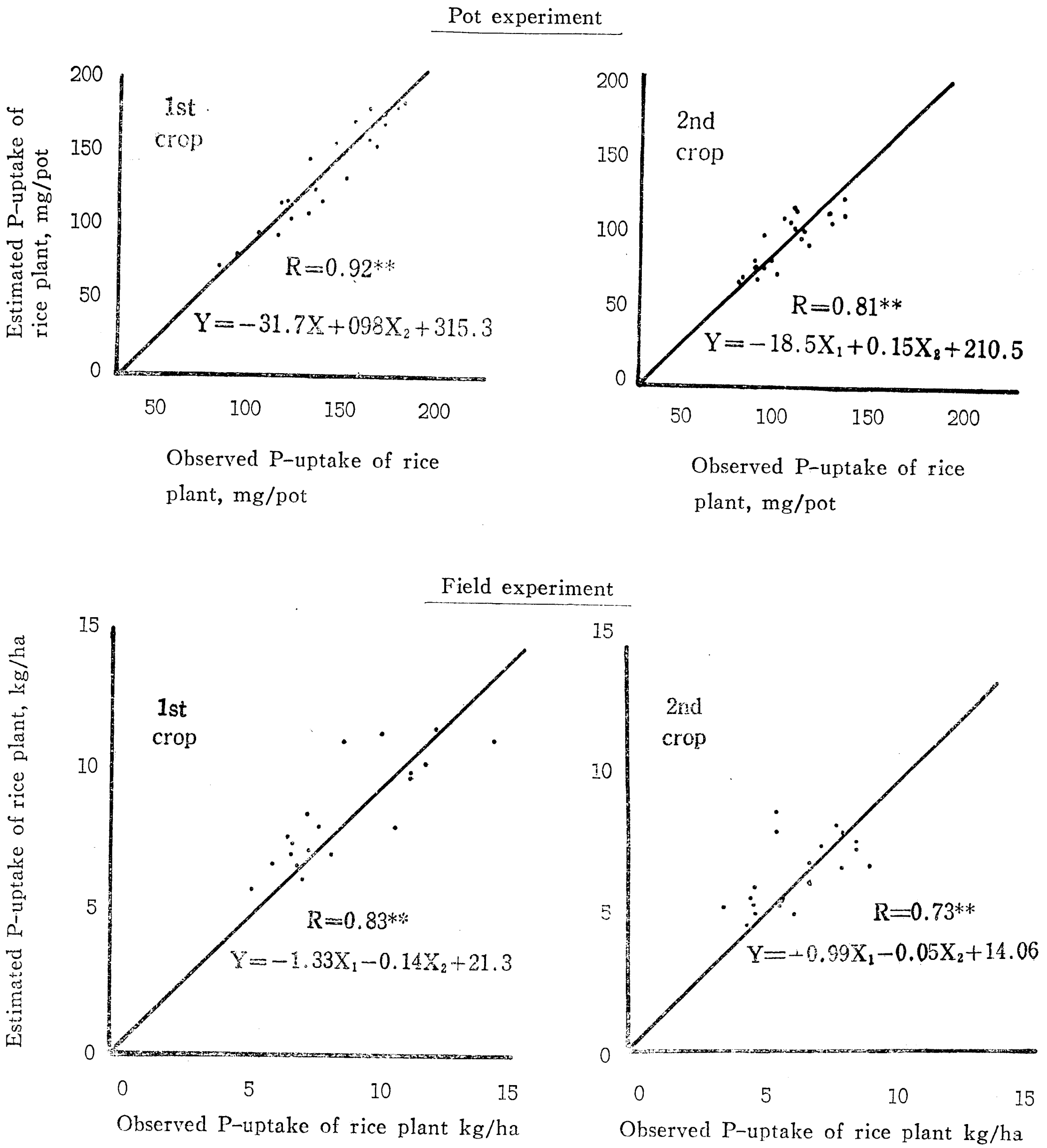


Fig. 4. Dot charts showing observation and estimation for equation :

$$Y=-aX_1 \pm bX_2+C$$

Y=P-uptake, X_1=pH , X_2=Clay

Clay×Organic matter）之複相關係數與二因子者相若，從圖4.示在施磷情形下由水稻磷吸取量與土壤 pH 及 Clay 之複迴歸關係所估計之水稻磷吸取量與實測值極為接近，尤以盆栽為然， 由此顯示水稻對於磷之攝取，不僅受土壤中磷形態之影響，亦受土壤 pH 與粘土含量之控制， 對於利用土壤磷速測值估計稻田磷肥供應時，土壤化學性狀尤應加以考慮。

誌　　謝

本研究獲得國家科學委員會研究補助費及中國農村復興聯合委員會補助試驗經費。供試土壤承陳技正春泉選取鑑定、程式統計承李技正蘭蒂設計，謹致謝忱。

參 考 文 獻

1. Al-Abbas, A. H., and Barber, S. A. 1964. A soil test for phosphorus based upon fractionation of soil phosphorus : (1) Correlation of soil phosphorus fraction with plant available phosphorus. SSSA Pro. 28 (2) : 218—224.
2. Asam, T., and Kumada, K. 1959. A new method for determining free iron oxide in paddy soils. Soil and Plant Food., 5 (3) : 141—146.
3. Black, C. A. (Editor in chief) 1965. Methods of soil analysis, Part 2. No. 9 in the series of Agronomy published by the American Society of Agronomy.
4. Chang, S. C., and M. L. Jackson 1957. Fractionation of soil pnospnorus. soil sci. 84. (2) .
5. Chang, S. C., and W. K. Chu, 1960. Forms of phosphorus in the soils of Taiwan. Jour. Agr. Assoc. China. New Series, No. 30.
6. Chang, S. C., and W. K. Chu, 1959. Radioactive assay of the availability of soil phosphorus in lowland rice soils. Proc. of Third Japan Conference on Radioisotopes.
7. Chang, S. C. 1965. Application of phosphorus fractionation to the study of Chemstry of available soil phosphorus. Soils and Fertilizers in Taiwan.
8. Chang, S. C. 1976. Phosphorus in submerged soils and phosphorus nutrition and fertilization of rice (Manuscript) presented at Seminar on the Fertility of Paddy soils. Food and Fertilizer Technology Center for the Asian and Pacific Region, Taiwan, Republic of China.
9. Chu, W. K., and S. C. Chang. 1966. Surface activity of inorganic phosphorus. Soil Sci. 101 (6) .
10. Ezekiel, M. and Fox, A. K. 1972. Methods of correlation and regression analysis 3rd ed.
11 Watrick, W. H. Jr. and D. S. Mikkelsen 1972. Plant nutrient behavior in flooded soils. Fertilizer and Technology and Use. 2nd Ed.
12. Susuki, A. K., Lawtons, and Doll, E. C. 1963. Phosphorus uptake and soil tests as related to forms of phosphorus in some Michigan soils. SSSA Proc. 27 : 401—403.

13. 林家棻、張愛華、曾肇清 1970 土壤中不同形態磷含量與作物對於磷肥效應之關係 中華農學會報告第69期。
14. 林家棻 1969 本省現行之土壤肥力測定法 臺灣省土壤肥力速測工作人員訓練班講義。
15. 林家棻 1963 植物分析方法與應用 平鎮茶試所報告 No. 16.
16. 李子純、林家琨、林家棻 1974 中部粘板岩冲積土性質與水稻生長及產量之關係 農業研究 Vol. 23, No. 4.

GRAIN YIELD AND P-UPTAKE OF RICE PLANT AS RELATED TO P-FRACTION IN THE SOILS OF CENTRAL TAIWAN

by

C. F. Lin, A. H. Chang, W. K. Wu

Summary

The application of phosphorus fractionation to the study of plant available phosphorus has been applied by several workers. However, most of them were conducted in pot culture. Information regarding the response of rice plant to various forms of soil phosphorus in field conditions is still in meager. This experiment was carried out for understanding the relationship of soil P-fraction to grain yield as well as P-uptake of rice plant under both pot culture and field conditions in order to find out the behavior of soil phosphorus between them. Twenty field trials were conducted on four categories of alluvial soils (sandstone and shale alluvial soil, slate older alluvial soil, slate recent alluvial soil, and mixed alluvial soil) scattered in central Taiwan. Soil samples for pot culture were taken from the sites where field trials had been carried out. The result may be summarized as follows :

1. The analysis of total phosphorus content showed that slate alluvial soil was the highest, sandstone and shale alluvial soil, the second, and mixed alluvial, the third.

2. The result of soil phosphorus fractionation indicated that the slate alluvail soils were dominant in Ca—P, the sandstone and shale alluvial soils in Fe—P, and the mixed alluvial soils in both Ca—P and Fe—P. The Al—P and organic—P occupied in the range of 4—7 % and 14—20% of the total phosphorus of the soils, respectively. It was also found that the amount of various forms of soil phosphorus had much to do with the nature of the soils, such as pH, clay, organic matter, CEC, exchangeable Ca and Mg, and free iron oxides. It was worthwhile to mention that remarkably positive correlation was found between soil Ca-P and soil pH, and between soil organic—P and clay.

3. In comparing the change in the amount of total phosphorus and various forms of phosphorus before and after 4 consecutive cropping of rice in pot culture, it was found that the content of total phosphorus was higher in the soils treated with phosphorus but lower in the soils received no phosphorus. The Ca-P almost remained constant in the soil without phosphorus, but increased in the soils with phosphorus. The increase in organic-P was also found in the soils with phosphorus. The other forms of phosphorus including Al-P, Fe-P, and occluded-P decreased, more or less in all soils regardless whether phosphorus had been added or not . Although the transformation of various forms of soil phosphorus is influenced by the nature of the soil and cultural practices, highly positive correlation between P-uptake and Fe-P reduced in the soil treated with-

out phosphorus after cropping was obtained. It provided the evidence that Fe--P was the main source of phosphate absorbed by rice plant under submerged condition.

4. The results of simple and multiple correlation of soil phosphorus to P-uptake also indicated that soil Fe-P was the main source of phosphate absorbed by rice plant. On the contrary, soil Ca-P was negatively correlated with P-uptake under both pot culture and field conditions. Furthermore, significantly negative correlation between P-uptake and soil organic-P was also found in field conditions. Consequently, the relative importance of soil Fe-P increasing P-uptake was minimized in field conditions.

5. Negatively close relationship of P-uptake to soil pH was found in both pot culture and field conditions. In addition, contents of clay and organic matter were also negatively correlated with P-uptake in field conditions at significant level. As mentioned before, soil Ca-P and organic-P was positively correlated respectively with soil pH and clay. Thus the inhibition of P-uptake of rice plant by Ca-P and organic-P may be attributed to pH and clay content of the soils tested.

In conclusion, phosphorus uptake of rice plant was highly related to soil Fe-P in pot culture provided without drainage, but less in field conditions. It is due probably to the difference in the function of clay and organic matter between them.